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Laser Drilling of Via Micro-holes in Single-crystal Semiconductor Substrates using a 1070 nm Fibre Laser with Millisecond Pulse Widths

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ABSTRACT

Micro-machining of semiconductors is relevant to fabrication challenges within the semiconductor industry. For via holes for solar cells, laser drilling potentially avoids deep plasma etching which requires sophisticated equipment and corrosive, high purity gases. Other applications include backside loading of cold atoms into atom chips and ion traps for quantum physics research, for which holes through the semiconductor substrate are needed. Laser drilling, exploiting the melt ejection material removal mechanism, is used industrially for drilling hard to machine materials such as superalloys. Lasers of the kind used in this work typically form holes with diameters of 100's of microns and depths of a few millimetres in metals. Laser drilling of semiconductors typically uses short pulses of UV or long wavelength IR to achieve holes as small as 50 microns. A combination of material processes occurs including laser absorption, heating, melting, vaporization with vapour and dust particle ejection and resolidification. An investigation using materials with different fundamental material parameters allows the suitability of any given laser for the processing of semiconductors to be determined. We report results on the characterization of via holes drilled using a 2000 W maximum power 1070 nm fibre laser with 1-20 ms pulses using single crystal silicon, gallium arsenide and sapphire. Holes were characterised in cross-section and plan view. Significantly, relatively long pulses were effective even for wide bandgap substrates which are nominally transparent at 1070 nm. Examination of drilled samples revealed holes had been successfully generated in all materials via melt ejection.
Keywords: laser drilling, semiconductor, hole, via, metal wrap thru, laser, 1 micron wavelength, silicon, sapphire, gallium arsenide, wafer

1. INTRODUCTION

The application of holes of dimension tens of microns in semiconductor substrates is widespread in the domains of silicon-based solar cells, as holes for metal wrap-thru [2], and in Monolithic Microwave Integrated Circuits (MMIC's) also to create low resistance connections between the front and back wafer surfaces. Via electrical interconnects have particular application in environments where compactness and low weight are at a premium, such as in space applications. Further applications are the manufacture of uniformly sized holes for the introduction of vapour fluxes and such holes and interconnects find application in quantum sensors such as ultra-cold atom experiments and ion trapping experiments [3].
The material removal mechanism is known to depend on the pulse length, with short pulses, i.e. in the range of ns or fs, generally producing vaporization and longer pulses drilling via a melt ejection mechanism. Melt ejection is the more energy efficient material removal mechanism, reported as requiring, for metals, approximately 25% of the energy per unit volume compared to vaporization. The majority of laser drilling carried out in semiconductor materials uses short pulses [4, 5], with ultra-violet[6] lasers being the most widely used. Some longer pulse work has been done Yu et al. [7] used 6.6 µs 1070 nm pulses to drill silicon. Longer wavelength lasers have also been used: Li and O'Neill using 1 µm radiation to drill silicon [8]; polycrystalline alumina has previously been laser drilled with ms 1064 nm pulses [9], as well as µs 10.6 µm pulses [10]. Laser drilling of GaAs for radiation detectors and power devices has been reported for short pulse (ns and fs) percussion drilling using wavelengths in the range of 263-1064 nm [11-13], with the shorter wavelengths reported as more efficient [12]. Li et al.[14] drilled alumina wafers with ns ultraviolet and fs near infrared lasers, with the fs laser producing cleaner, crack-free holes.
Under low optical intensities, absorption in semiconductors depends on the bandgap, with only photons of energies exceeding the bandgap being absorbed. It is well known that interfaces lead to scattering and absorption, making some nominally transparent materials opaque, which explains the successful long wavelength laser drilling of alumina[9] [10]. For single crystal wafers however the relevant sub-bandgap absorption results from distortion of the bandgap due to impurities or structural imperfections as well as some absorption being attributable to free carriers [15].

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We report a study of the laser drilling of semiconductor wafer substrates using a 1 micron fibre laser capable of delivering a power of up to 2000 W in pulses of minimum length 1 ms. Typical laser parameters which have been used are shown in Table 1. The substrate materials were single crystal, single-side polished epitaxial wafers and have high melting points in comparison with more commonly laser-machined metals such as steels. An argon assist gas was used during drilling.

2. EXPERIMENTAL METHOD

A 2 kW IPG YLR-2000 multimode Nd:YAG fibre laser with a wavelength of approximately 1070 nm was used throughout this work. A 200 µm diameter delivery fibre and a Precitec YK52 cutting head with a 125 mm collimation length and a 120 mm focal length lens produced a focused spot size of 192 µm on the top surface of the drilled samples. Argon assist gas was delivered coaxially to the laser beam, via a nozzle with a 1 mm exit diameter 1 mm above the sample surface. Laser parameters used are given in Table 1. For each combination of parameters 9 individual holes were drilled with a 2 mm spacing maintained between adjacent holes.

Table 1. Laser Drilling Parameters

IPG Laser (wavelength 1.07 µm)			
Power	300 – 2000 W	Assist gas	Argon, 0.5-2 bar
Pulse length	10 ms		

Three different semiconductor wafer substrate materials were used in this work: Al_2O_3 (sapphire), gallium arsenide (GaAs) and silicon (Si). All samples were single crystal 2 inch diameter wafers, 0.5 mm thick with one polished and one unpolished side. Surface roughness of the polished side was typically 0.5 nm R_{rms} and the unpolished side was 1 µm R_{rms}. Such material samples are of high purity being grown as single crystals from a melt of purity 99.9999%. Samples were used as received ("epiready"). Relevant material properties are summarised in Table 2. By comparing the bandgap energies to that associated with the wavelength used, 1.2 eV it can be seen that sapphire, with a significantly larger bandgap energy [13], is transparent and Si is opaque whereas GaAs has a bandgap slightly greater than the photon energy. Sapphire may be approximated as a direct bandgap insulator as the difference between indirect and direct gaps is small and measured experimental values of the bandgap range from 8.7 eV to 9.4 eV [16]. The term volume energy is used to indicate the energy required to heat unit volume of material to the melting point and melt it.

Table 2. Comparison of some relevant semiconductor wafer material parameters

Material		Parameter (at room temperature)	
Sapphire	(Al2O3)	semiconductor bandgap	8.7 eV [1]
		melting point	2040 °C
		specific heat capacity	1195 $J\,kg^{-1}\,K^{-1}$
		density	3.97 g cm^{-3}
		volume energy 44.9	kJ cm^{-3}
Silicon	(Si)	semiconductor bandgap	1.1 eV
		melting point	1410 °C
		specific heat capacity	712 $J\,kg^{-1}\,K^{-1}$
		density	2.33 g cm^{-3}
		volume energy 161.1	kJ cm^{-3}
Gallium Arsenide	(GaAs)	semiconductor bandgap	1.4 eV
		melting point	1240 °C
		specific heat capacity	350 $J\,kg^{-1}\,K^{-1}$
		density	5.3 g cm
		volume energy 18.6	kJ cm^{-3}

Drilled holes were examined using optical microscopy, hole dimensions were determined by image analysis using a precision of ± 5 µm. The results presented are averages of the 9 holes for each parameter set. Cross-sectional images were obtained by optical microscopy after mounting wafer fragments in standard metallographic polymer mounts and polishing in order to reveal the approximate mid-plane of the hole.

3. RESULTS

The holes drilled in this work have dimensions of hundreds of micrometers, entrance diameters range from 180 µm to 510 µm whereas exit diameters range from 140 µm to 500 µm. The majority of the exit diameters are between 160 µm to 300 µm. As shown in Figure 1a the majority of holes are tapered, with the entrance diameter being larger than the exit diameter, the exception being the Al_2O_3 results. Figure 1b shows that while the exit hole is smaller than the entrance hole for both surface finishes of Si drilled with the same conditions, the surface finish does affect hole dimensions. The entrance hole for the unpolished material is 25% larger than that of the polished material, there no significant difference between the sizes of the exit holes. The larger standard deviation seen in the entrance holes for Si needs further investigation given the small number of holes in the sample size used here. There are clear manufacturing reasons to be interested in the effect of surface state on both the absolute dimensions and reproducibility of the holes produced.

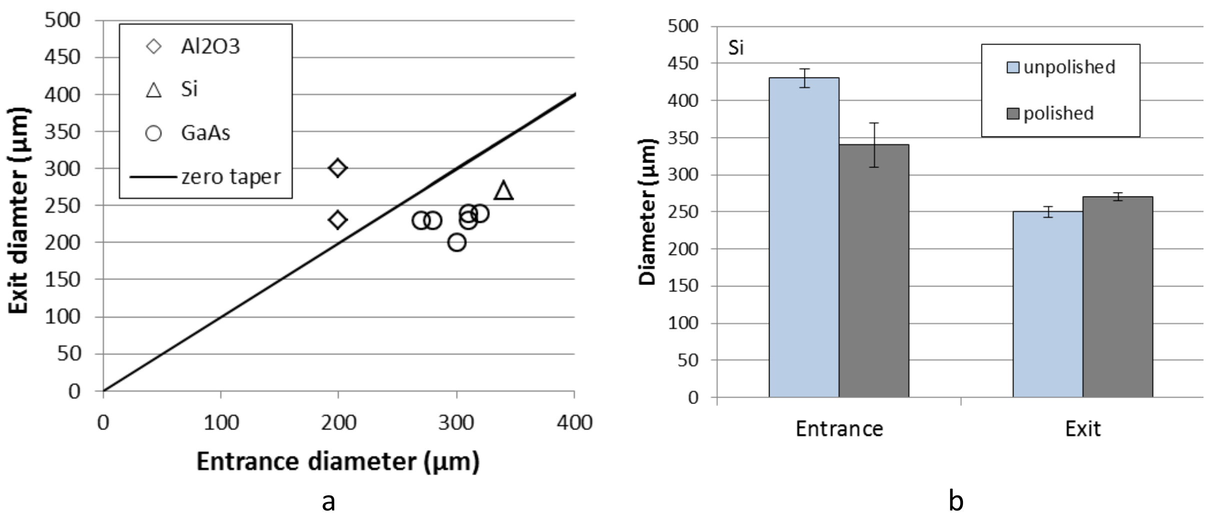

Figure 1 a: Average entrance and exit diameters for all holes drilled, note that each data point for a given material corresponds to a different set of drilling parameters, b: Comparison of hole dimensions for drilling of Si with two different surface finishes using single, 10 ms 1000 W pulses and 0.5 bar assist gas.

For all materials, resolidified melt was seen around the entrance and exit holes (Figure 2a) in addition resolidified spatter was observed to have been distributed across the drilled surface. Cross-sectional observations (
Figure 2 c) reveal cracking associated with the recast layer lining the holes. For Si another form of damage was observed, this was the cross pattern of lines seen in
Figure 2e, which formed on the rear side of the wafer below the site of a hole which did not penetrate through the full thickness of the wafer.

As seen in Figure 3 there is generally little variation in hole dimensions with power for the parameters used. The Al_2O_3 results again stand out as being the only case where the exit hole is greater than the entrance hole, i.e. a negative taper. Increasing assist gas pressure decreases both entrance and exit diameters, the extent of the effect decreases with increasing pressure.

Figure 3 also reveals variation as a function of sample type. The holes drilled in Al_2O_3 have the smallest entrance diameter, approximately 60% of those seen in GaAs and Si.

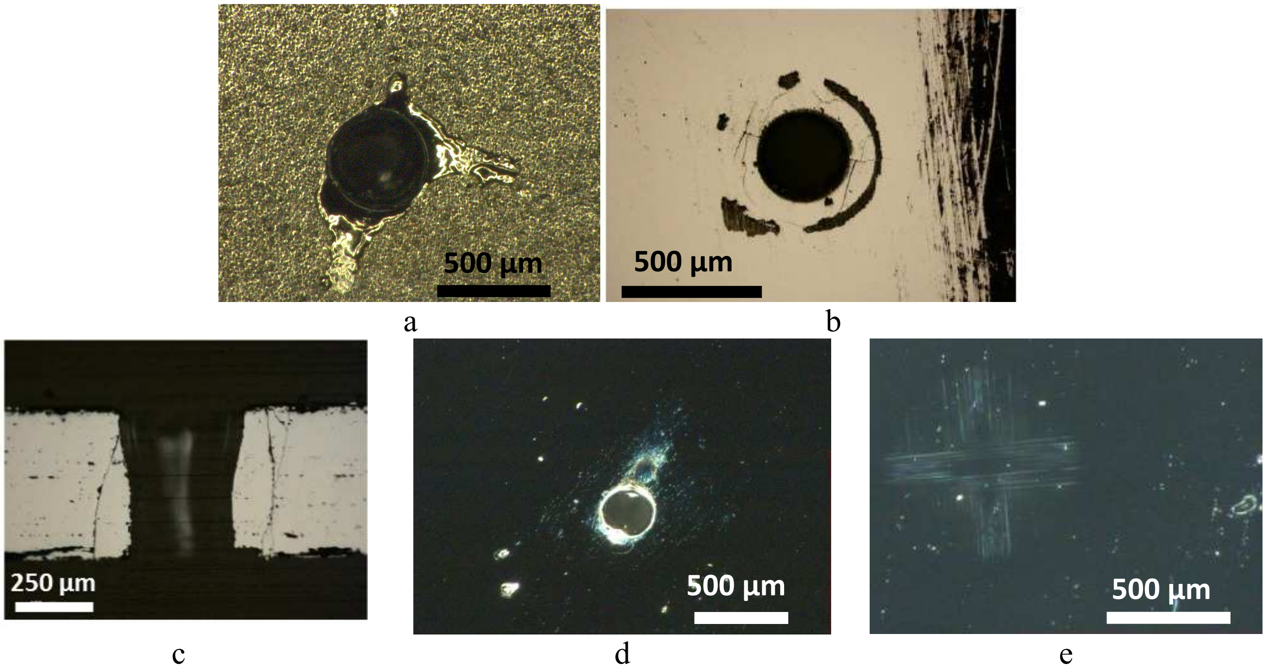

Figure 2 Optical micrographs of features associated with laser drilled holes a: resolidified material around entrance of hole drilled in Si, b: cracking around entrance hole on GaAs, c: cracking associated with recast layer in Si, d: exit hole on Si e: cross pattern seen on rear side of drilling site on Si.

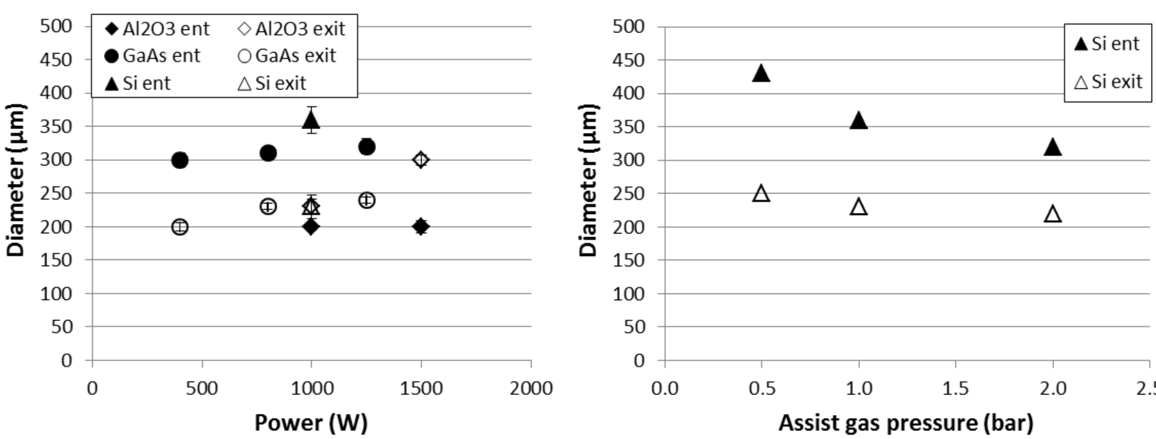

Figure 3 Variation of exit and entrance diameters for single, 10 ms pulses drilled from polished side with a: power using 1 bar assist gas, b: assist gas pressure for a power of 1000 W.

4. DISCUSSION

The presence of resolidified spatter on the surface as well as immediately surrounding the hole confirmed that laser drilling occurred here via the melt ejection mechanism of material removal. It is notable that holes have been successfully drilled in all materials, including Al_2O_3 which is expected to be transparent to the 1070 nm laser irradiation used due to its large bandgap. One point of note is the relatively small variation in hole dimensions as a function of material type despite the significant variation in relevant material properties (Table 2). The pulse length of 10 ms delivered of the order of 15 J and this exceeded the volume energy necessary for melting the material ejected from the all holes. A study of lower pulse energies may reveal greater characteristic differences between materials. There will be a temperature dependence of the various material properties, resulting in a temporal evolution which would be of interest to monitor. Yu et al. [17] have reported positive feedback in temperature dependent absorption in silicon, resulting in enhanced absorption. It is possible that such a mechanism affects all three materials considered here, however further work is needed to confirm this.

The generation of any cracks in the resolidified layer is a concern in any material, but particularly so in brittle materials such as semiconductors. Examination of drilled samples in this work revealed the presence of cracking in the region of material immediately adjacent to the hole, i.e. in the materials associated with the resolidified layer. It should be noted that all the holes drilled in this work were generated using single pulses so there is interest in extending this work to multiple pulse drilling in order to determine whether the thermal shock associated with successive pulses drives catastrophic growth of these cracks.

The cross-pattern observed in Si is attributed to slip damage as has been previously observed in laser irradiated single crystal Si by Choi and Jhang [18]. In their work, which irradiated a Si wafer without inducing melting, similar features were observed on the top, irradiated, surface for irradiances greater than 230 W cm^{-2}. While the irradiances used in this work are significantly higher, it seems clear that the same mechanism is active, i.e. the stresses induced by constrained thermal expansion due to laser irradiation have locally exceeded the critical resolved shear stress.

It is suggested that the unpolished surface leads to enhanced surface absorption of light for a surface roughness of the order of the wavelength of the light. A key result to note is that holes have been successfully drilled in all materials, including Al_2O_3 which is expected to be transparent to the 1070 nm laser irradiation used due to its large bandgap. It is suggested that localised absorption centres randomly dispersed throughout the volume are responsible for absorption in this material.

In summary, the feasibility of long pulse 1 μm laser drilling has been demonstrated for these semiconductor wafer substrate materials.

5. CONCLUSIONS

The results demonstrate that the laser used in this work is appropriate for drilling holes with diameters of the orders of hundreds of microns in semiconductor wafers via the melt ejection mechanism. Hole sizes were within a factor of 2 of the beam waist size of 200 microns. Long pulses were useful for these materials in contrast to many published reports of the necessity of ultra-short pulses.

Multiple holes were drilled in single crystal wafers which remained robust and allowed the preparation of cross-sections by polishing without catastrophic failure. These brittle substrates did show some cracking but the cracks did not propagate during sample preparation.

Absorption of the intense electromagnetic radiation occurs within the volume of the wider bandgap material via the excitation of lattice vibrations (phonons) within the crystal volume. The difference between the polished and unpolished surfaces showed that surface absorption effects are more significant for narrower bandgap materials.

In general there is little variation in hole dimensions with power and the standard deviations of entrance and exit hole size are low, at < 5 %.

6. FUTURE WORK

An investigation of the percussion drilling of these brittle materials, where multiple pulses are incident on the same location, should be carried out since there is a possibility that the thermal shock associated with successive laser pulses may induce growth of any cracks within the resolidified layer. There is also interest in exploiting the lower total energy input typical of percussion drilling to minimize damage. Future work will also include using a different fibre laser to generate similar power densities but with a smaller ~ 30 μm spot size.

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